Grasp Mapping Between a 3-Finger Haptic Device and a Robotic Hand

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Abstract. This paper presents the implementation of a robust grasp mapping between a 3-finger haptic device (master) and a robotic hand (slave). Mapping is based on a grasp equivalence defined considering the manipulation capabilities of the master and slave devices. The metrics that translate the human hand gesture to the robotic hand workspace are obtained through an analytical user study. This allows a natural control of the robotic hand. The grasp mapping is accomplished defining 4 control modes that encapsulate all the grasps gestures considered.
Transition between modes guarantee collision-free movements and no damage to grasped objects. Detection of contact with objects is done by means of customized tactile sensors based on MEMS barometers.
The methodology herein presented can be extended for controlling a wide range of different robotic hands with the 3-finger haptic device.

Keywords: Grasp mapping, haptic device, robotic hand, tactile sensors

1 Introduction

The definition of a grasp taxonomy for a multi-finger haptic device that allows controlling robotic hands presents a great challenge due to the wide range of available configurations (3-finger, 4-finger, 5-finger).

The aim of this work is to obtain an intuitive grasp mapping for a 3-finger haptic device [1] that allows us to control a wide range of robotic hands.
Haptic devices have been extensively used in teleoperation due to an increase in the immersion [2] and to a faster reaction time to unexpected force events [3, 4].

Most prior approaches [5, 6] focused on essentially anthropomorphic hands, where mapping at the finger level is most appropriate. Here, the focus is on mapping between functional grasps of specific object classes. This can be applied to map between completely different numbers and postures of fingers, so highly dissimilar master and slave hands can be used.

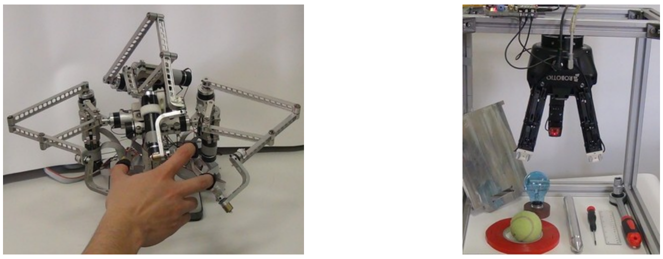
The proposed mapping is based on Cutkosky and Howe [7] and Feix *et al.* [8] taxonomies. This paper argues that it is possible to cover several grasps in the human hand workspace with only 3 fingers and specifically knowing only the position of the *thumb*, *middle* and *index* fingers. Previous works [9] have shown that the model of the human hand can be simplified from 24 to 9 DoFs with a 10% error.

Performing mechanical optimization of the number of tasks that a robotic hand can accomplish while reducing the number of DoF and hence its cost and complexity, often leads to non-anthropomorphic designs.

However, the hand gesture in the human hand space should be mapped to another gesture at the robotic hand grasp space. This requires an initial study of the hand morphology through simulation or real experiments that calculates what is the most appropriate gesture to grasp a specific type of object.

This paper is organized as follows. Section 2 describes the experimental setup used for evaluation. Section 3 explains the proposed grasp mapping between the 3-finger haptic device space and the robotic hand space. Section 4 presents the results obtained from the experiments carried out. Finally, conclusions are summarized in section 5.

2 Experimental Setup



(a) 3-Finger Haptic Device (b) Robotiq Hand

Fig. 1: Experimental setup: The robotic hand is located facing down.

The experimental setup (Fig. 1) consists of a 3-finger haptic device acting as master that controls a robotic 3-finger hand acting as slave. The robotic hand (Fig. 1b) is located facing down in order to asses stable grasps [10].

2.1 3-Finger Haptic Device

The 3-finger haptic device shown in Fig. 1a has 10 actuators and 19 DoFs for movements. Each finger has its own mechanical structure with 6 DoFs.
The first 3 are actuated and allow reflecting forces to the user in any direction. The last 3 allow to reach and measure any orientation within the device workspace. The mechanical structures of the 3 fingers are linked to the base through a redundant actuated joint that increases the workspace which results in a shape similar to a torus [1].

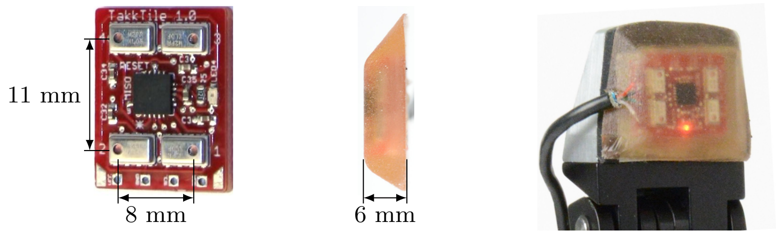
Finger tip positions are calculated from the actuators encoders. Orientations can be obtained from encoders located at the gimbal rotations.

2.2 Robotic Hand

The robotic hand shown in Fig. 1b is the 3-finger adaptive robot gripper by Robotiq[4]. It has 4 actuators and 10 DoFs with under-actuated design that allows the fingers to automatically adapt to the grasped object shape and also simplifies the control.

2.3 Takktile Sensors

The tactile sensing system is based on MEMS Barometers encapsulated in rubber, and vacuum-degassed to provide a direct transmission between surface and sensor [11] (TakkTile LLC, Cambridge, MA). This approach provides sensitive and robust feedback while the outline of the sensors could be easily customized. The sensors are developed for the fingertips of the gripper as these are the points of initial contact during manipulation.



(a) MEMS barometers (b) Cast sensor (c) Fingertip mounting

Fig. 2: TakkTile sensors for Robotiq Adaptive Gripper.

Four MPL115A2 MEMS barometers (Freescale, Austin, TX) along with an ATtiny24 microcontroller (Atmel, San Jose, CA) are mounted on a custom PCB. The barometers spacing provides effective sensing over the pad of the fingertip under 6mm rubber (see Fig. 2). The microcontroller is embedded to provide chip-select function during sampling. The sensors are cast in urethane rubber (Vytaflex 20, Smoothon Inc.) in custom designed molds.
The pressure readings are zeroed immediately before each grasp to eliminate thermal drift.

3 Grasp Mapping

The hand gesture in the human hand space – captured by the 3-finger haptic device – should be mapped to another gesture in the robotic hand grasp space.

Table 1 shows the proposed grasp mapping between the master and slave devices. In total we suggest 12 possible grasps based on the taxonomies proposed by Cutkosky and Howe [7] and Feix *et al.* [8].

[4] `http://robotiq.com/`

Table 1: Equivalent grasps between the haptic device and the robotic hand

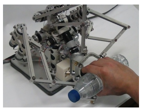
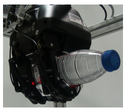
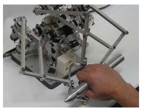
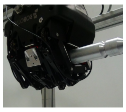
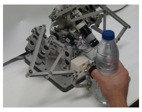
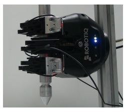
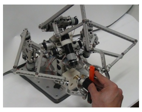
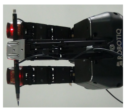
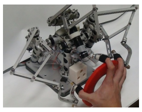
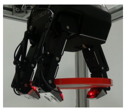
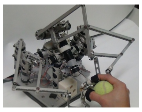
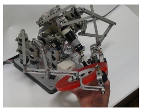
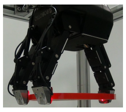
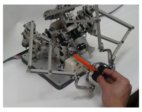
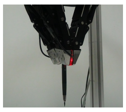
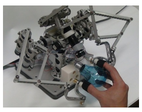
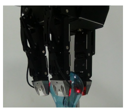
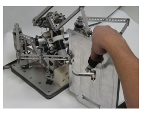
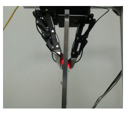
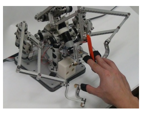
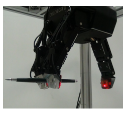
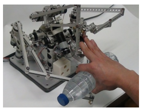
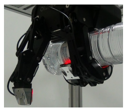
	Name	3-Finger Device	Robotiq Hand	Type	Gesture
1	Large Diameter			Power	Basic
2	Small Diameter			Power	Basic
3	Medium Wrap			Power	Basic
4	Prismatic 2-Finger			Precision	Basic
5	Power Disk			Power	Basic
6	Power Sphere			Power	Basic
7	Precision Disk			Precision	Basic
8	Palmar Pinch			Precision	Pinch
9	Precision Sphere			Precision	Pinch
10	Parallel Extension			Precision	Pinch
11	Adduction Grip			Precision	Scissor

Table 1: (Continued)

12	Ring			Power	Ring

Theses grasps are chosen considering the capabilities of the robotic hand. The hand can perform them in a stable manner [10] with only 3 fingers thanks to its under-actuated design.

3.1 Grasp Identification: User Study

In order to identify the intended grasp an analytical user study is performed. Moreover, the grasp has to be detected in the early stages of the approaching movement so that the control of the robotic hand can configure the gesture mode before starting to move.

Five users wearing the 3-finger haptic device – without any experience with the device and no prior knowledge about grasping taxonomies – repeat 50 times 4 different grasping gestures that encapsulate all the proposed grasps in Table 1: Basic, Pinch, Scissor and Ring.

Each user opens the hand, then closes to grasp the object and finally opens again to continue with the next grasp.

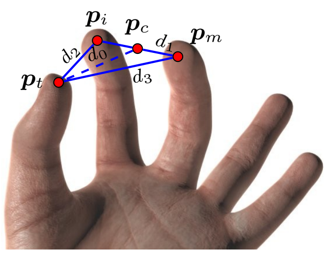


Fig. 3: Metrics used for the grasp identification.

Metrics Since the user can grasp at any point of the haptic device workspace, relative distances between the fingers are used, see Fig. 3 and Equation (1). Furthermore, every person has different hand size, hence it's convenient to normalize these distances between 0 and 1, see Equation (2).

$$\boldsymbol{p}_c = \frac{(\boldsymbol{p}_m - \boldsymbol{p}_i)}{2} \; .$$

$$d_0 = \|\boldsymbol{p}_c - \boldsymbol{p}_t\| \quad d_1 = \|\boldsymbol{p}_m - \boldsymbol{p}_i\| \quad d_2 = \|\boldsymbol{p}_i - \boldsymbol{p}_t\| \quad d_3 = \|\boldsymbol{p}_m - \boldsymbol{p}_t\| \; . \tag{1}$$

$$\hat{x} = \frac{x - \min\|\boldsymbol{x}\|}{\max\|\boldsymbol{x}\| - \min\|\boldsymbol{x}\|} \; . \tag{2}$$

Grasp Detection We detect the grasp using a simplified approach that considers the distances d_1, d_2 and d_3. Moreover, from the area – Equation (3) – of the triangle formed between the fingers it is possible to determine when the grasp starts and ends.

$$A = \sqrt{s\,(s - d_1)\,(s - d_2)\,(s - d_3)} \qquad \text{with} \qquad s = \frac{d_1 + d_2 + d_3}{2} \tag{3}$$

Figure 4 shows 5 grasps for all the studied gestures. For each grasp the start and end point is shown. The grasps are segmented detecting the zero crossing point of the area derivative $\frac{dA}{dt}$. This derivative is calculated using a digital low-pass differentiator [12] with a constant window of 100 ms.

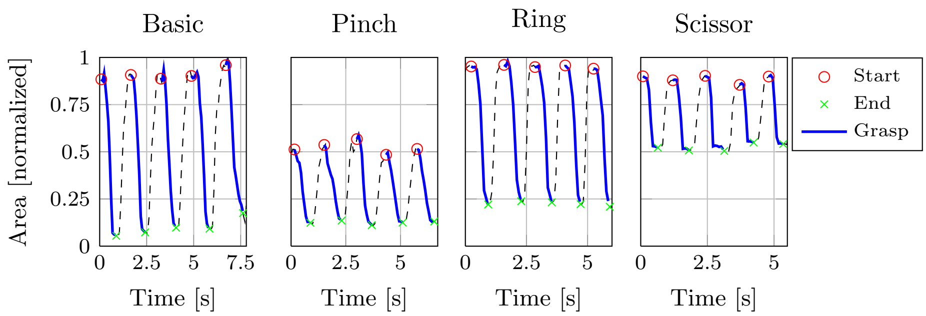


Fig. 4: The grasp detection is done using the area of the triangle formed between the 3 fingers.

The grasp starts when the area derivative crosses zero going negative and ends when crosses zero going positive.

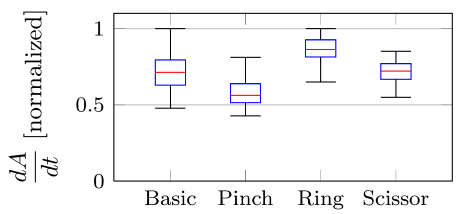


Fig. 5: Area derivative values at the grasp start for all the gestures.

Figure 5 shows a box plot of the area derivative when the grasp starts. It can be seen that for all the gestures it is possible to choose a threshold (0.4 in our application) for detecting in real-time when the grasp starts.

3.2 Robotic Hand Control

The 3-finger robotic hand behaves in an anthropomorphic way but cannot perform some of the transitions while avoiding collisions between the fingers. For

example, in a change from ③ Medium Wrap to ⑤ Palmar Pinch the *middle* and *index* fingers will collide. The human hand lacks of this problem because the fingers can be overlapped.
Figure 6 shows the proposed control modes:

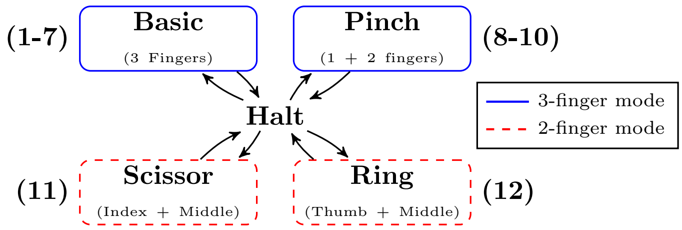


Fig. 6: Grasp modes. Numbers correspond to the grasps in Table 1.

Halt Starts when the user opens the hand, then monitors the area derivative until it exceeds the detection threshold and depending on the finger velocities $\dot{\boldsymbol{p}}_t$, $\dot{\boldsymbol{p}}_m$ and $\dot{\boldsymbol{p}}_i$ selects the control mode that corresponds to the user intention.

Basic Mode Covers 7 of the 12 possible grasps. In this 3-finger mode the opening/closing is mapped to the distance d_0. The distance between the *middle* and *index* fingers is fixed to avoid finger collisions. The differentiation between power and precision grasp is accomplish using the position where the tactile sensors detect the contact.

Pinch Mode 3-finger mode useful to perform precision grasps of small objects. Similar to the *Basic Mode* the opening/closing is mapped to the distance d_0. The *middle* and *index* fingers move together to act as one big finger.

Scissor Mode The *middle* and *index* fingers act as a scissor in this 2-finger mode. The opening/closing is mapped to the distance d_1. This mode lacks of tactile feedback due to the location of the tactile sensors.

Ring Mode The user can perform equivalent grasps to those achievable using a classic 2-finger gripper. It uses the *thumb* and *middle* fingers and therefore the opening/closing is mapped to the distance d_3.

4 Results and Discussion

In order to validate the robustness of the grasp identification algorithm an experiment of 360 different samples has been carried out.
Six users – without any training and no experience with the haptic device – perform 60 random grasps, 15 for each control mode.

Table 2: Results of the grasp identification, 94.7% of the samples are correctly classified.

Grasps	**Predicted group membership**			
	Basic [%]	Pinch [%]	Ring [%]	Scissor [%]
Basic	90	0	10	0
Pinch	0	100	0	0
Ring	8.9	0	91.1	0
Scissor	2.2	0	0	97.8

The proposed method classifies correctly 94.7% of the samples with a confidence level of 99%. Table 2 shows the percentage of efficiency for each grasp identification.

The relationship among the predicted group membership and the intended grasp shows an important error between Basic and Ring grasps. This error is due to the *index* and *middle* fingers coupling that results in similar movements with the only difference been that Basic is a 3-finger mode and Ring is a 2-finger mode.

Depending on the application, the use of the Ring gesture can be avoided to increase the classification efficiency up to 97.8%. Other alternative can include force readings from the 3-finger haptic device to improve the discrimination given that the force exerted by the *index* finger during the Ring grasp is almost zero.

5 Conclusions

This paper presents an efficient connexion between a 3-finger haptic device and a robotic hand. This connection is based on a robust grasp mapping that can be extended to dissimilar master and slave hands. The results reveal that exists sufficient separation between the two larger groups – Basic and Pinch – which allows to discriminate them clearly.

The grasp identification is based on the results of an analytical user study. The algorithm identifies the grasp in the early stage of the approaching movement using a time window of 100 ms. This fast reaction time allows the robotic hand to change the grasp mode before starting to move.

The proposed method classifies correctly 94.7% of the samples and depending on the application this percentage of efficiency can be increased up to 97.8%. All users that performed the experiments had no experience with the haptic device and no prior knowledge about grasping taxonomies, which suggest that a natural control of the robotic hand is accomplished.

Finally, the combination of the grasp identification and control modes allows collision-free movements and coherent force feedback to the user while interacting with grasped objects.

Acknowledgements

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